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Demonstration and Validation of Advanced Rebar Materials in Salt-Exposure Applications

Final Report on Project F09-AR13

Steven C. Sweeney, Orange S. Marshall, John Taylor, Lawrence Clark, and Rick Miles

October 2017

Construction Engineering Research Laboratory

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Demonstration and Validation of Advanced Rebar Materials in Salt-Exposure Applications

Final Report on Project F09-AR13

Steven C. Sweeney and Orange S. Marshall

Construction Engineering Research Laboratory
U.S. Army Engineer Research and Development Center
2902 Newmark Drive
Champaign, IL 61822

John Taylor, Lawrence Clark, and Rick Miles

Mandaree Enterprise Corporation (MEC)
812 Park Drive
Warner Robins, GA 31088

Final report

Prepared for Office of the Secretary of Defense (OUSD(AT&L))
Washington, DC 20301-3090

Under Project F09-AR13, "Evaluation of State-of-the-Art Rebar Concrete Structures in Salt Environments at Fort Knox, KY"

Abstract

Military installations maintain networks of roads and bridges that comprise basic, mission-critical infrastructure required for everyday operations. Many reinforced concrete bridges are long overdue for repair or replacement due to various stressors and corrosion mechanisms that have degraded the steel reinforcement and, therefore, reduced load-carrying capacity. These stressors include cyclic loading, freeze/thaw cycles, and penetration of water and road deicing salts that greatly accelerate both corrosion and concrete fracturing. This report presents the findings of a demonstration/validation project at Fort Knox, KY, in which two different advanced corrosion-resistant reinforcement materials were used in reconstructed concrete bridge decks.

Material performance was monitored for 18 months using sensors to return data on corrosion potential, corrosion rate, and chloride penetration thresholds. These data also were collected from a control structure reinforced with conventional carbon steel rebar, and analyses were executed to compare material performance. Exposure testing of material specimens in highly corrosive environments was performed concurrently. Both demonstrated rebar materials have shown good corrosion resistance in the bridge decks and exposure coupon racks. Continuing periodic observation of the demonstration structures is recommended to produce more definitive performance results. Economic analysis of both materials show a positive return on investment over carbon steel rebar.

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Preface

This demonstration was performed for the Office of the Secretary of Defense (OSD) under Department of Defense (DoD) Corrosion Prevention and Control (CPC) Project F09-AR13, "Evaluation of State-of-the-Art Rebar Concrete Structures in Salt Environments at Fort Knox, Kentucky." The proponent was the U.S. Army Office of the Assistant Chief of Staff for Installation Management (ACSIM), and the stakeholder was the U.S. Army Installation Management Command (IMCOM). The technical monitors were Daniel J. Dunmire (OUSD(AT&L)), Bernie Rodriguez (IMPW-FM), and Valerie D. Hines (DAIM-ODF).

The work was performed by the Materials and Structures Branch of the Facilities Division (CEERD-CFM), U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL), Champaign, IL. Michael K. McInerney, CEERD-CFM, was the ERDC CPC Program Coordinator. At the time this report was prepared, the Chief of the ERDC-CERL Materials and Structures Branch was Vicki L. Van Blaricum (CEERD-CFM), the Chief of the Facilities Division was Donald K. Hicks (CEERD-CF), and Kurt Kinnevan, CEERD-CZT, was the Technical Director for Adaptive and Resilient Installations. The Interim Deputy Director of ERDC-CERL was Michelle J. Hanson, and the Interim Director was Dr. Kirankumar Topurdurti.

Tom Hutchins, Fort Knox Department of Public Works (DPW), is gratefully acknowledged for his support and assistance in this project.

The Commander of ERDC was COL Bryan S. Green, and the Director was Dr. David W. Pittman.

Unit Conversion Factors

Multiply	By	To Obtain
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
gallons (U.S. liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
mils	0.0254	millimeters
square feet	0.09290304	square meters

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1 Introduction

1.1 Problem statement

The Department of Defense (DoD) is responsible for construction and maintenance of more than 1,500 bridges to traverse streams, ravines, and rivers so support ordinary operations and military missions. The current technology employed in concrete bridge infrastructure typically has a 50-year design life; however, according to the Illinois and New York state departments of transportation—representing two states where road salts are used extensively for deicing—the average service life of a steel-reinforced concrete bridge deck is 25 years (Hastak, Halpin, and Hong 2004). This corrosion problem affects many DoD bridges. For example, the Army's bridge safety program inventory shows that more than 80% of its bridges employ standard steel, concrete, or steel and concrete construction (Dean 2008). Of those, bridges located in areas where road deicing salts are used in winter deteriorate prematurely as chlorides penetrate the concrete and accelerate steel-corrosion processes. The *Annual Cost of Corrosion for the Facilities and Infrastructure of the Department Of Defense* lists road surfaces, of which bridge decks are a subset, as having the highest total corrosion cost based on facility category (Herzberg 2014).

A major impact of accelerated corrosion is creating excessive stress on concrete when accretions of iron oxide expand the diameter of embedded reinforcing bar (rebar) by up to 40%. This major expansion results in cracking and spalling of concrete that deteriorates roadway surfaces and significantly increases maintenance costs. Major roadwork on bridges is costly and interferes with installation traffic and operations. Ongoing accelerated rebar corrosion can quickly degrade structural integrity and cause premature infrastructure failure, which greatly increases life-cycle costs. This accelerated corrosion is not limited to vehicle infrastructure located in cold regions; it also affects reinforced concrete buildings and other structures worldwide, especially those located close to marine coastlines.

In previous infrastructure projects sponsored by the DoD Corrosion Prevention and Control (CPC) Program, advanced materials such as composites have been demonstrated and validated as alternatives to conventional concrete with carbon steel rebar in highly corrosive environments

(Sweeney et al. 2016a, 2016b). The project reported here investigated concrete surfaces that were designed with two advanced steel-based materials as a substitute for carbon steel rebar.

1.2 Objective

This project was designed to test the viability of two new types of corrosion-resistant materials, fabricated in the form of conventional concrete reinforcing bar for use in concrete structures located in high-chloride environments. The following two new materials were tested:

- MMFX2™ (martensitic microscopic microstructure), a micro-composite martensitic ferritic steel that has a carbide-free microstructure.*
- Nuovinox rebar, a composite product with a carbon steel core, clad with grade 316 L stainless steel.†

1.3 Approach

Fort Knox, Kentucky, was chosen as the site for this evaluation, where rehabilitation of bridges was being done throughout the installation. While not typically a high snowfall location, Fort Knox has occasional ice and snow storms and routinely uses salts for deicing. The need for rehabilitation was principally a result of the corrosion of rebar and steel structures that compromised the integrity of many of the bridges.

1.4 Metrics

Three types of sensors were installed to monitor the performance metrics of the reinforcement in this field demonstration. Chloride penetration sensors were used to determine exactly how deep chlorides were absorbed into the various concrete rebar structures and to see if chlorides reached the reinforcing steel during the evaluation period. Corrosion potential sensors were used to measure the electrical potential in the concrete to determine if corrosion was likely to occur. Finally, corrosion rate sensors were used to measure the intensity of corrosion occurring. In addition, an evaluation was performed of the handling and constructability of the different materials used as part of the demonstration.

* Manufactured by MMFX Steel of Irvin, CA.

† A product of Stelax Industries, Ltd. of Dallas, TX.

In addition to the field demonstration, a nonstandard exposure test was conducted by placing samples of each material used in the demonstration on a corrosion exposure rack at an extreme exposure site in Hawaii. The site is on the northern shore of Oahu and subject to constant salt water spray and high temperatures (Figure 1). Each specimen was bent 180 degrees prior to exposure. This nonstandard test was performed to visually observe the relative corrosion resistance of the materials and whether bending the materials impacted their corrosion resistance.

Figure 1. Exposure test site in Hawaii.

2 Technical Investigation

2.1 Project overview

This project procured and evaluated two emerging technologies for corrosion-resistant rebar material in concrete. A third structure was built with conventional carbon steel rebar as a control. These structures were designed and installed by the Fort Knox Directorate of Public Works (DPW) during 2009. Various sensors were installed and monitored by contractor MEC. The test materials conformed to all specifications in the design plans.

Two different types of bridges that were already being rehabilitated by Fort Knox were used as the project's test sites. The project's control site consisted of concrete pavement to emulate a bridge deck because the third bridge, anticipated to be used as a control for the project, was not going to be constructed at the time of project implementation. Bridge 9 (see Figure 5 on page 7) was constructed with martensitic microcomposite microstructure (MMFX) rebar. Bridge 42 (see Figure 7 on page 9) was constructed with standard steel rebar clad with 316L stainless steel. While Bridge 42 is not a typical bridge, it was what was being rehabilitated by Fort Knox and thus, it was made a part of this project. The substituted control site was the entrance to Hurley Tank Motor Maintenance Facility, which was constructed with standard carbon steel rebar embedded in the pavement's eight concrete slabs, each 9.5 in. thick.

To study the corrosion-resistant properties of the test materials, various sensors were installed during the rehabilitation of the bridges and concrete slab. The sensors were installed at critical locations to measure minimum and maximum effects on the rebar. Initial readings at each structure were taken shortly after construction to form baseline conditions of the rebar before initial corrosion could occur. Conditions were then monitored monthly for a period of 18 months to determine if initial corrosion had commenced and if so, to what degree.

Measurements were taken by utilizing three different types of sensors that are described briefly in the following paragraphs.

To measure corrosion potential, Stelth 7 silver/silver chloride reference electrodes* were placed at strategic locations across the structure. Potential measurements could then be obtained and monitored for corrosion activity over a stated period of time. The reference electrodes were attached directly to the rebar and mounted as shown in Figure 2.

Figure 2. Corrosion potential reference electrodes (blue).

To measure corrosion rate, Rohrback Cosasco Systems (RCS) 800 Linear Polarization Resistance (LPR) Corrater® probes† were used (Figure 3). These sensors were directly attached to the rebar being tested. The sensors have dual probes fitted with the material under test, and instantaneous corrosion rates of steel in concrete can then be obtained and recorded.

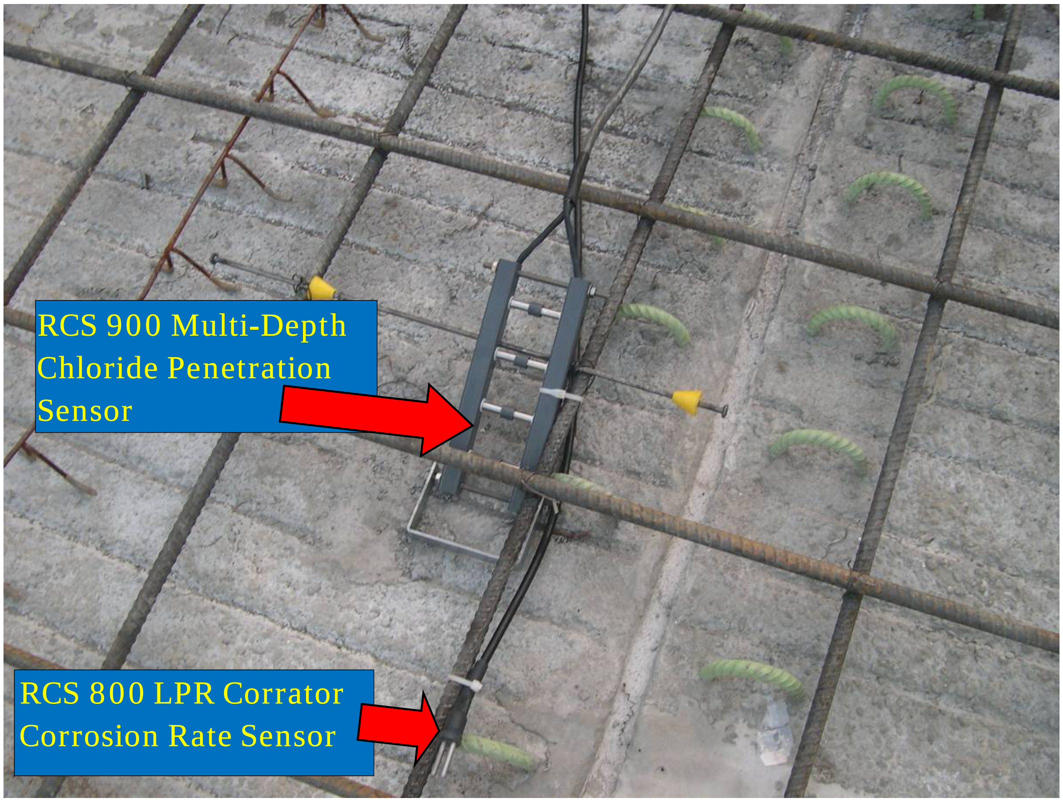
To determine chloride ion penetration from deicing salts, the RCS 900 Concrete Multi-Depth Sensor was utilized (Figure 3). This sensor is a ladder-type probe that can be adjusted to measure ingress of chlorides at different levels. This ladder sensor was adjusted to measure from 1 in. to 4 in.

* A product of Borin Manufacturing, Inc. of Culver City, CA,

† Corrater is a legacy brand of the company now known only as Cosasco, with headquarters in Santa Fe Springs, CA.

below the concrete surface. This adjustable measurement capability allows for monitoring chlorides as they progress through the concrete strata.

Figure 3. Corrosion rate sensor and multidepth chloride penetration sensor.



All data from the three types of sensors were monitored monthly from initiation to completion of the project. Bridges 9 and 42 were completed first (October 2009) and were monitored from 24 October 2009 to 20 March 2011.. The concrete slab at Hurley Tank Motor Park (the control site) was completed in December 2009. Initial measurements of it were taken 16 December 2009 and completed 20 March 2011.

As previously stated, one material tested was MMFX2 rebar (Figure 4). This material was installed in Bridge 9, a conventional steel beam structure with a poured concrete cap. However, the replacement bridge used precast, reinforced, stressed beams with a concrete deck cap that was constructed using the MMFX rebar (Figure 5). Sensors were installed in the deck cap at five locations. A deck cap's thickness varied from 4 to 7 in. and had a brushed concrete veneer.

Figure 4. Samples of MMFX2 rebar installed at Bridge 9.

Figure 5. Bridge 9 prior to project initiation, a conventional steel beam structure with a poured concrete deck.

A second material tested was a 316L stainless steel-cladding (SSC) on standard carbon steel rebar (Figure 6). This material was tested on Bridge 42, a box culvert configuration (Figure 7). The concrete box portion of the bridge was constructed using the SSC rebar, then covered with 18 in. of dirt and rock. A 5 in. asphalt cap was installed at the road surface. Three sets of sensors were embedded in the concrete box structure to measure data from the SSC rebar that was buried under dirt and rock (Figure 8). Corrosion potential sensors were installed in this area with stainless steel coupons in the reference electrode. The corrosion rate sensor and multi-depth penetration chloride sensors were installed in the same area. To emulate the testing done on Bridge 9 for chloride penetration, a 3 x 10 ft concrete slab (see Figure 28 on page 26) was poured and installed in the road surface, using SSC rebar along with the three types of sensors. The sensors were installed in the same configuration as Bridge 9, but with two sets of sensors. The only variance in sensor type was the corrosion potential reference electrodes installed in this area. Time constraints, due to construction timetables and procurement of the sensors, dictated that carbon steel coupon inserts had to be utilized in the corrosion potential reference electrodes.

Figure 6. 316L Stainless steel-clad rebar.

Figure 7. Bridge 42, a box culvert style, prior to project initiation.

Figure 8. Bridge 42 during construction.

Standard carbon steel rebar, serving as a control, was installed in a poured concrete slab at the south entrance of Hurley Tank Motor Park (Figure 9).

A third bridge was not going to be constructed at this time, so this concrete slab was considered to be a viable alternative to a bridge deck. The concrete slab was approximately 9.5 in. thick, with a standard configuration of steel rebar. Sensors were placed across the width of the site's south entry.

Figure 9. Carbon steel rebar installation at Hurley Tank Motor Park.

2.2 Rebar and sensor installation

The construction of Bridge 9 that used MMFX2 rebar was accomplished without any additional construction requirements. The MMFX2 was formed and cut on site in the same way as standard rebar. This is a distinct advantage over the 316 SSC rebar or even epoxy-coated rebar (not assessed in this project). The 316 SSC rebar had to be ordered prefabricated to all lengths and bends per the engineering drawings, a requirement that added to the expense of procuring the material for this project. This prefabrication was necessary because the SSC rebar can be damaged during bending and forming operations, exposing the carbon steel core. When cut, a cap must be epoxied onto the end of the SSC bar to seal it and prevent corrosion of the inner core material. The epoxy rebar that is a more common, standard, corrosion-resistant rebar experiences the same problems as the 316 SSC rebar, but the epoxy coating can be touched up and repaired in the field.

Sensor placements were done during the final pouring of concrete on the structures. Before the final concrete cap was poured on Bridge 9, corrosion potential and corrosion rate electrodes were installed directly to the rebar across the width of the bridge (Figure 10). The multidepth chloride penetration sensors were installed at the same location as the other electrodes. This ladder-type sensor (refer to closeup shown in Figure 3) was installed from 1 to 4 in. under the surface in 1 in. elevations. All sensor leads were bundled together on the north side of the bridge. The leads then traversed the bridge and terminated in a junction box on the west side of the bridge.

Figure 10. Bridge 9 sensor layout.

Bridge 42 has the same configuration of sensors as Bridge 9, but differs on the locations of the sensors. Three sets of sensors were installed in the poured concrete portion of the bridge, similar to Bridge 9. However, two sets of sensors were installed in the surface of the poured concrete pad that was installed later (Figure 11). All leads were bundled as they traverse the bridge and were terminated in a junction box located on the south side of the bridge.

Figure 11. Bridge 42 concrete pad sensor layout.

Sensors were installed during the final concrete pour across the south entrance of Hurley Tank Motor Park (refer to Figure 9 on page 10). The sensors were arrayed across the entrance at equidistant spacing and installed in the same configuration as the two bridges. All leads were bundled and terminated in a junction box situated on the southwest corner of the entrance gate.

It should be noted that the MMFX2 and SSC rebar installations were similar in nature to the installation of the carbon steel rebar and no special considerations had to be made for these installations.

2.3 Performance monitoring

The sensors were accessed and monitored at the corresponding junction boxes for each bridge (Figure 12 and Figure 13). The corrosion potentials were monitored by utilizing a high impedance multimeter in conjunction with the concrete-embedded corrosion potential silver-silver chloride reference electrodes. Potential measurements were obtained and recorded for the duration of the project. Corrosion rate monitoring was accomplished by connection of the corrosion rate dual probe sensor to an AquaMate™ Corrater* instrument. This instrument is manufactured by RCS and is designed to give instantaneous corrosion rates by the Linear Polarization

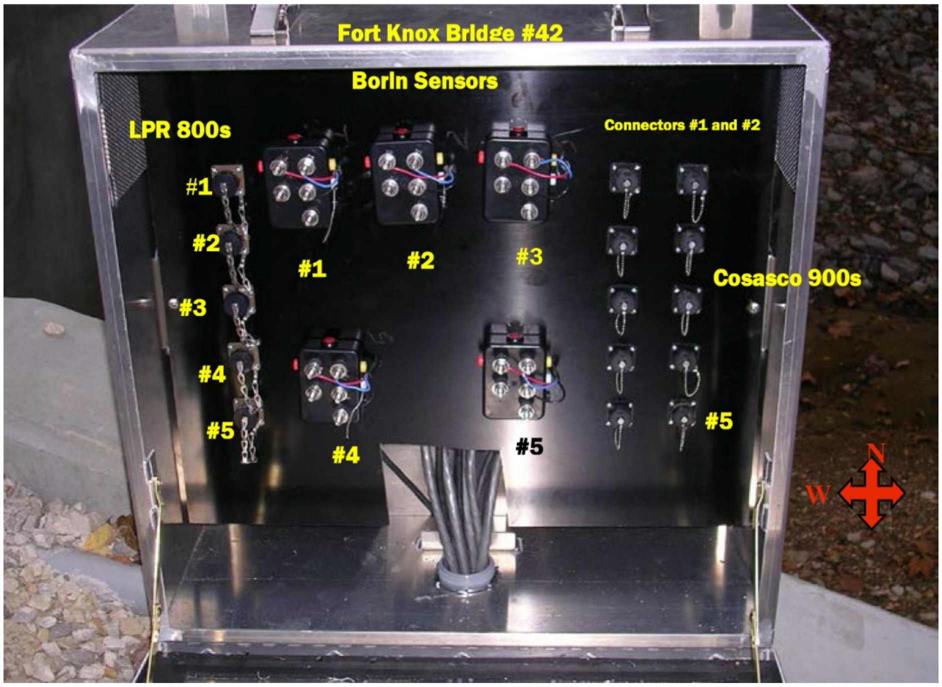
* Manufactured by RCS (now Cosasco).

Method and probe imbalances. Probe imbalances are an indication of corrosion and/or chloride penetration. Chloride penetration was recorded by utilizing the same instrument combined with a multidepth chloride penetration sensor ladder probe. Measurements were taken at four discrete levels, from 1 to 4 in. in depth.

Figure 12. Bridge 9 sensor junction box.

Initial measurements on all probes were obtained approximately 1 week after their installation at the three test sites. These measurements acted as base values to determine if corrosion activity was occurring on each tested material and at what rate. All data were then recorded and tabulated monthly at each location. There are no moving parts on this test project, and no additional maintenance is required. Sensors are expected to last well beyond the testing period.

Figure 13. Bridge 42 junction box layout.



2.4 Exposure specimens

A nonstandard exposure test was performed on samples of each rebar used in the demonstration project. The test's purpose was to subjectively evaluate the relative corrosion resistance between the materials, as well as to see if bending the materials had an adverse effect on their corrosion resistance. Approximately 1-foot long sections of size #5 bars were bent into a U shape with an approximate 2-inch radius. These samples were then placed on an exposure rack operated by the University of Hawaii on the north shore of the Oahu, Hawaii, at Marine Corp Base Hawaii (MCBH). The samples remained on the rack for 1,174 days, at which time the samples were removed, sealed in plastic bags, and shipped to ERDC CERL. The samples placed on the test rack are shown in Figure 14. In the figure, the SSC bar has the green tags, the MMFX2 samples the blue tag, and the plain rebar the orange tags.

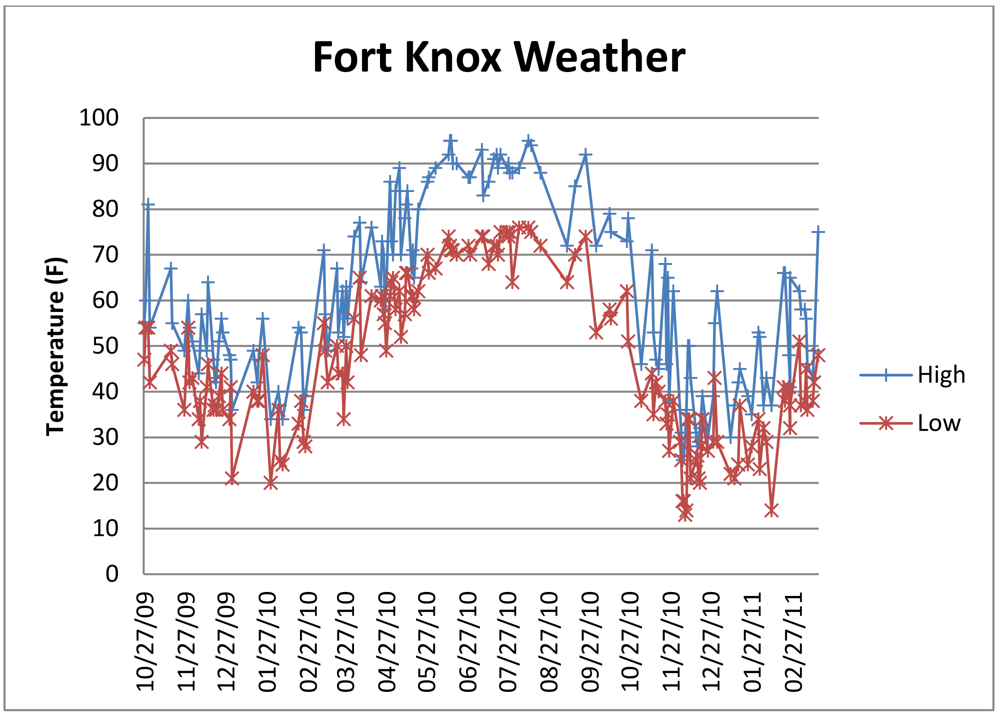
Figure 14. Sample rebar on test rack at MCBH.

3 Discussion

3.1 Results

Three temperature profiles and one precipitation profile for the duration of the project are given in Figure 15 through Figure 19.* The weather data was collected to see if there would be a correlation between it and the sensor data. Unfortunately, the 18-month performance period was not long enough to observe meaningful correlations between weather data and sensor data.

Figure 15. Fort Knox temperature profile for project duration.



* Project's duration was 27 October 2009 through 27 February 2011.

Figure 16. Temperature profile for Bridge 9 (MMFX2).

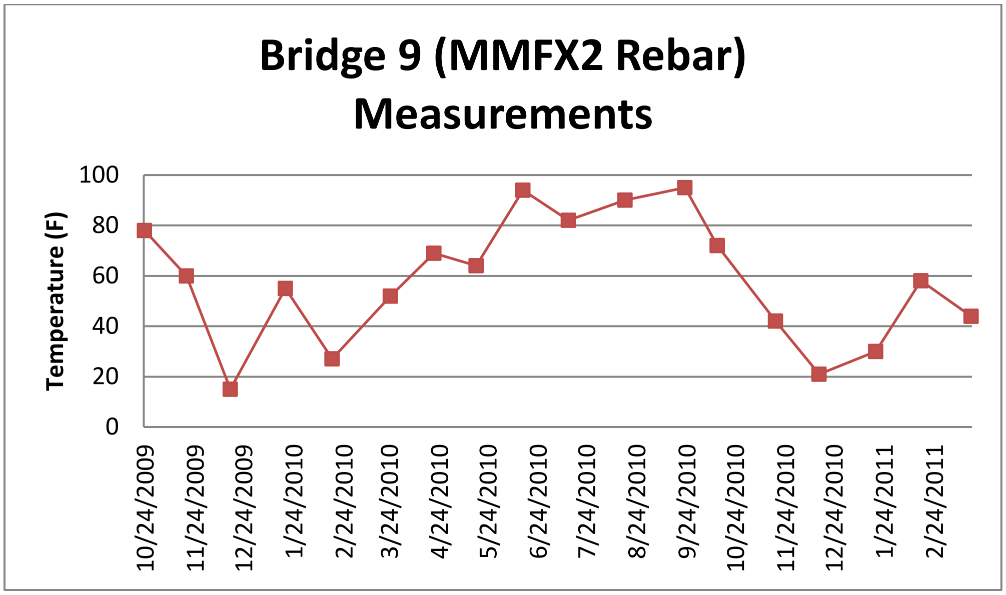


Figure 17. Temperature profile for Bridge 42 (316L SSC rebar).

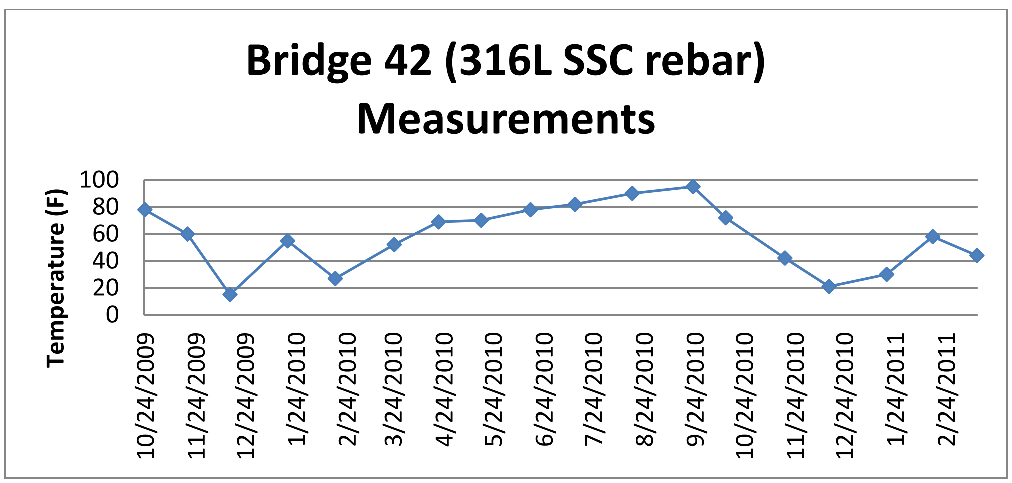


Figure 18. Temperature profile for Hurley Tank Motor Park concrete pad (standard carbon steel rebar).

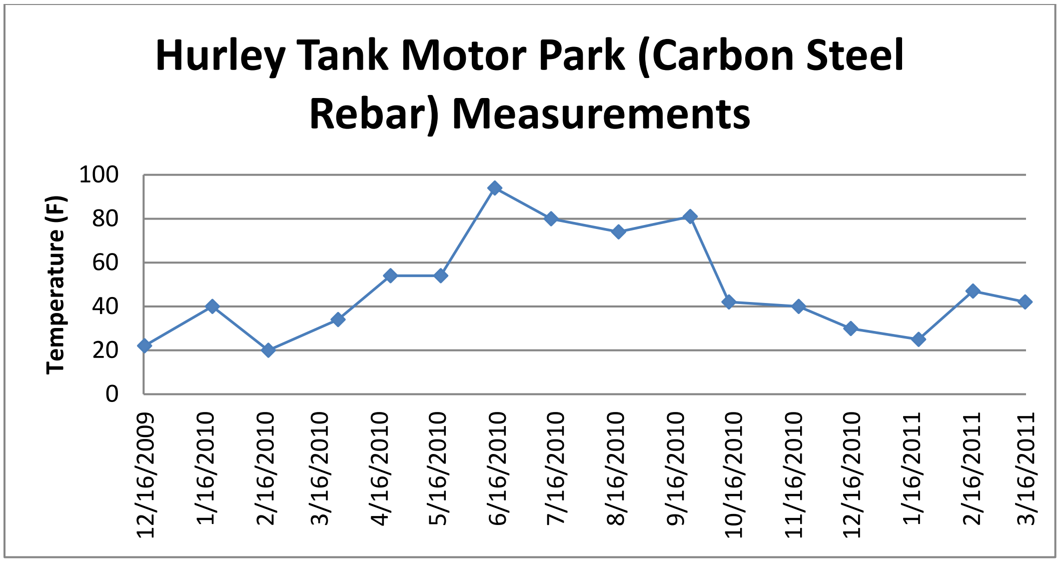
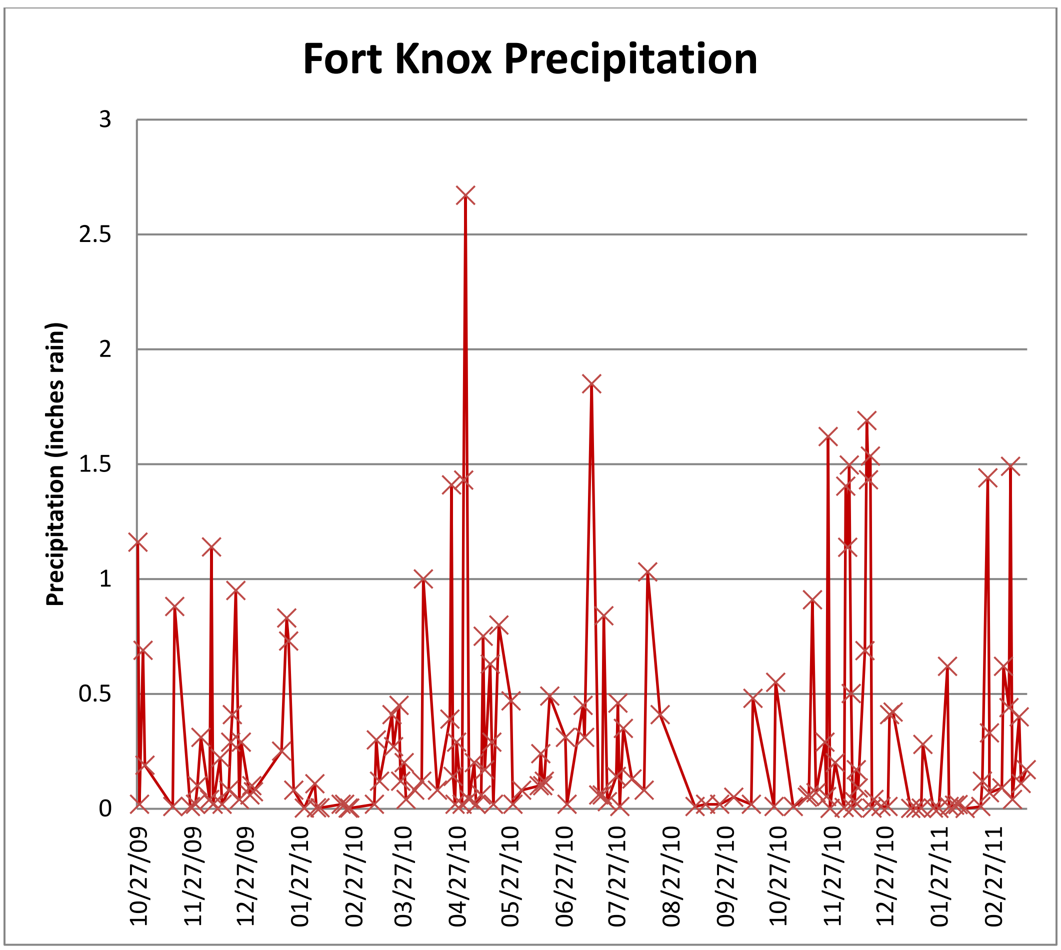


Figure 19. Fort Knox precipitation profile for project duration.



3.1.1 Corrosion potential measurements

According to ASTM C876, a potential more positive than -.2V is a good indication (90%) that corrosion is not occurring, and a potential more negative than -.35V is a good indication (90%) that corrosion is occurring (ASTM 2009). Corrosion potential measurements on Bridge 9 (Figure 20) were obtained using a silver/silver chloride reference electrode with an imbedded MMFX2 coupon of the bridge rebar material used during construction. The entire bridge deck was constructed with this rebar material. Initial potential measurements were in the range of -0.064 mV to -0.110 mV. The potentials noted were consistent with a non-cathodically protected metallic structure in a concrete environment. The first month, potential measurements elevated slightly then gradually lowered to around 0 (zero) mV and remained fairly constant since fall 2010. This finding would suggest that equilibrium has been achieved on the reference electrode and that corrosion activity is low to nonexistent.

Corrosion potential measurements on Bridge 42 (Figure 21) were obtained, similar to Bridge 9, but with a slight variation. This is the bridge constructed with 316L SSC rebar. All potential measurements were obtained with silver/silver chloride reference electrodes, but varied with respect to the embedded coupons. The lower concrete span had 316L SSC rebar embedded in the reference electrodes for a coupon, and they had a potential range of -0.031 mV to +.005 mV. This range is slightly lower than what was observed in Bridge 9. Potential measurements have decreased to around 0 mV and have remained relatively static for the last six months that measurements were taken. This finding suggests that this material has achieved a degree of equilibrium and that corrosion activity is very minor or nonexistent. The surface layer of this bridge was constructed of 18 in. of dirt and rock, with an asphalt cap. A concrete pad was installed, on the east side of the bridge, with SSC rebar. The reference electrodes in this area were constructed the same as those electrodes installed in the span, except they had carbon steel coupons instead. The carbon steel electrodes are more active, and this finding is indicative in the potential measurements. Potential measurements range from -0.082 mV to -0.151 mV initially. The potential measurements then have varied significantly. This variance is mainly seen on reference electrode 4 which has been salted since July 2010 (see Section 3.1.3). It would appear that corrosion activity may present on sensor 4, however it is still below the threshold identified in ASTM C876. Sensor 5 has remained fairly stable.

Corrosion potential measurements on the concrete slab at Hurley Tank Motor Park (Figure 22) were obtained in the same fashion as the two bridges. Silver/silver chloride reference electrodes with carbon steel coupons were installed across the south entrance gate. This concrete slab was constructed with conventional carbon steel rebar. Potential measurements initially obtained range from -0.019 mV to -0.533 mV. The potentials have been varying significantly monthly since startup, indicating that some corrosion activity may be occurring, with sensors 2 and 4 being the most active. Again, these measurements are still below the threshold identified in ASTM C876 for corrosion activity.

Figure 20. MMFX2 rebar corrosion potential measurements for Bridge 9.

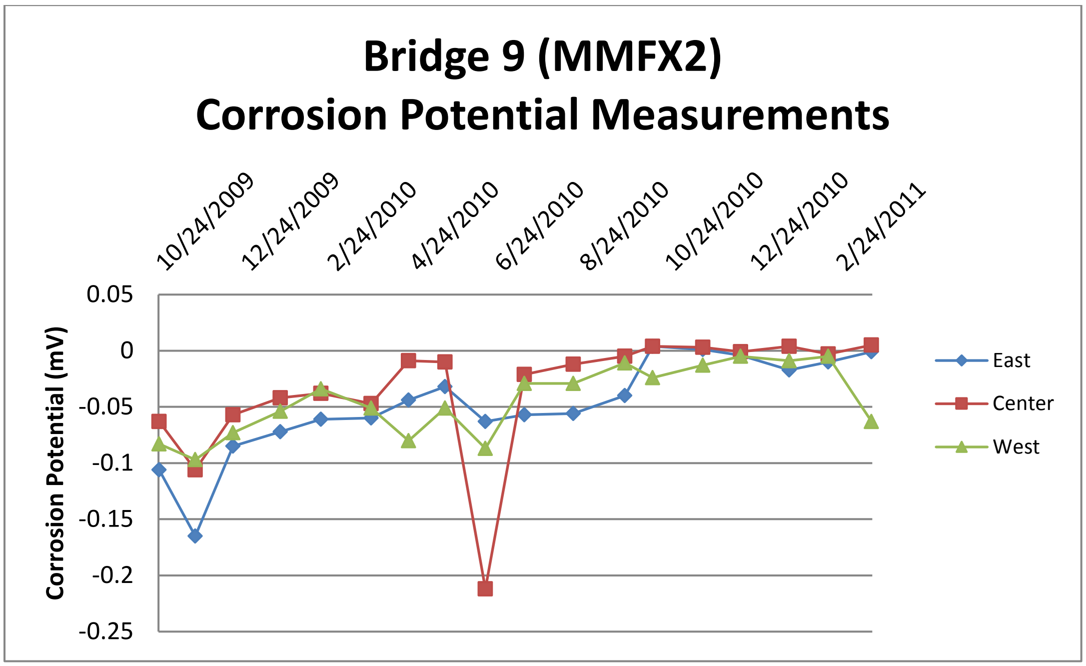


Figure 21. 316L stainless steel-clad rebar corrosion potential measurements for Bridge 42.

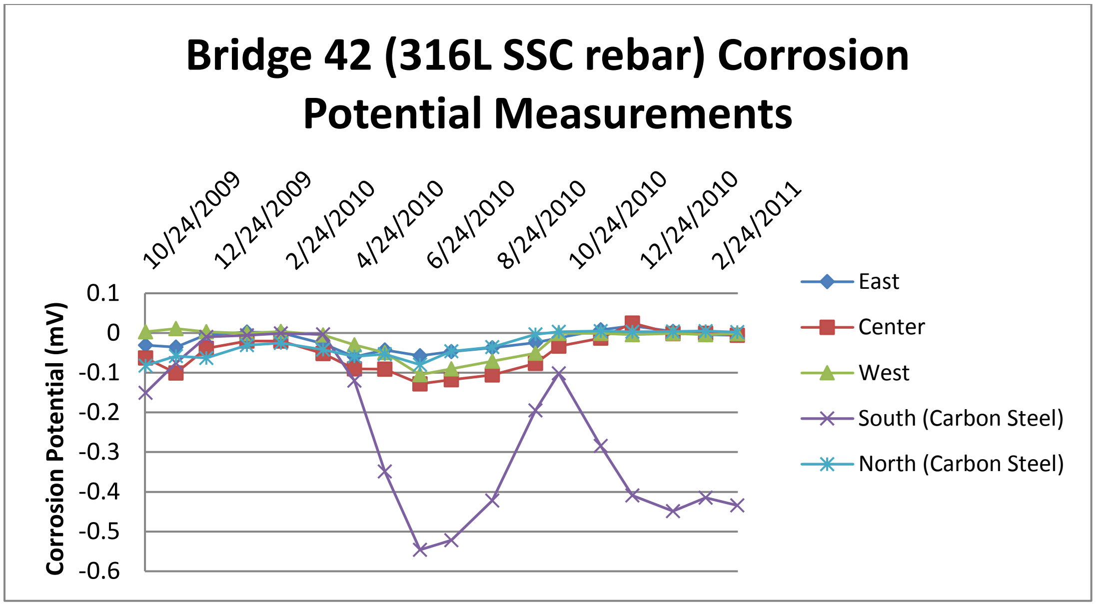
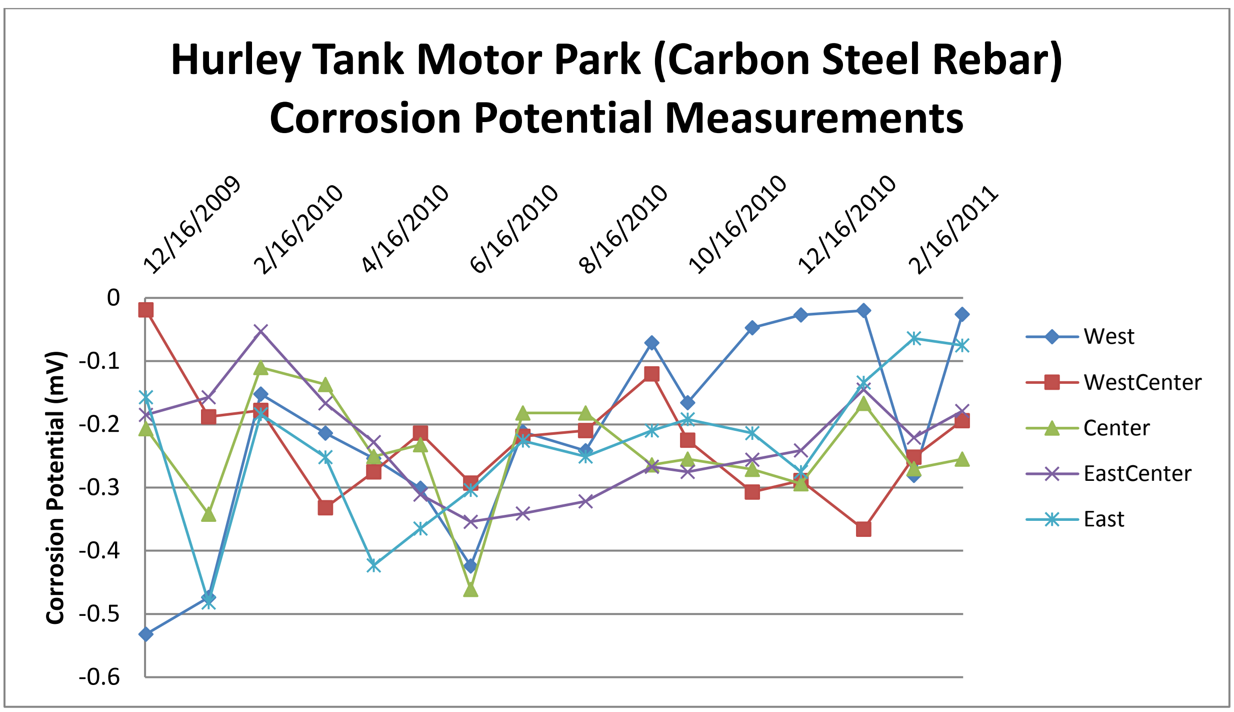


Figure 22. Carbon steel rebar (control) corrosion potential measurements for Hurley Tank Motor Park concrete pad.



3.1.2 Corrosion-rate measurements

Corrosion rate measurements obtained from Bridge 9 (Figure 23) were taken with the corrosion rate sensor instrument in conjunction with the corrosion potential sensor embedded in the concrete deck. Initial measurements indicated no activity on the dual probes for corrosion rate or imbalance. This condition remained stable during the duration of the testing period. No corrosion activity was indicated. The MMFX2 rebar material exhibited good corrosion resistance.

All corrosion rate measurements obtained on Bridge 42 (Figure 24) were taken in the same manner as for Bridge 9. Measurements indicate that no corrosion activity occurred on the bridge span or surface cap during the demonstration period. Measurements indicated slight changes at first, but they have stabilized and have remained stable. The 316L SSC rebar also showed good corrosion resistance.

Corrosion rate measurements obtained at Hurley Tank Motor Park (Figure 25) were taken in the same manner as for the two bridges. Initial readings showed little activity, but after four months, corrosion activity commenced and was observed for the duration of the testing period. Several months showed extensive corrosion activity, but other months indicated a much slower rate. Probe imbalance was particularly extensive for several months. Natural corrosion processes have started at this control site and will most likely accelerate over time.

Figure 23. MMFX2 rebar corrosion rate measurements for Bridge 9.

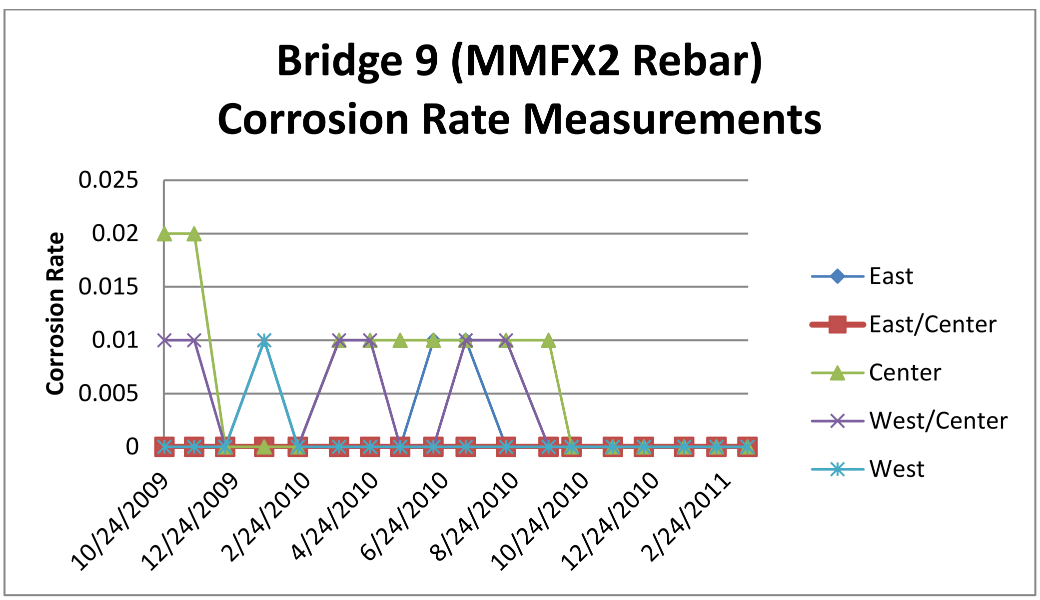


Figure 24. 316L stainless steel rebar corrosion rate measurements for Bridge 42.

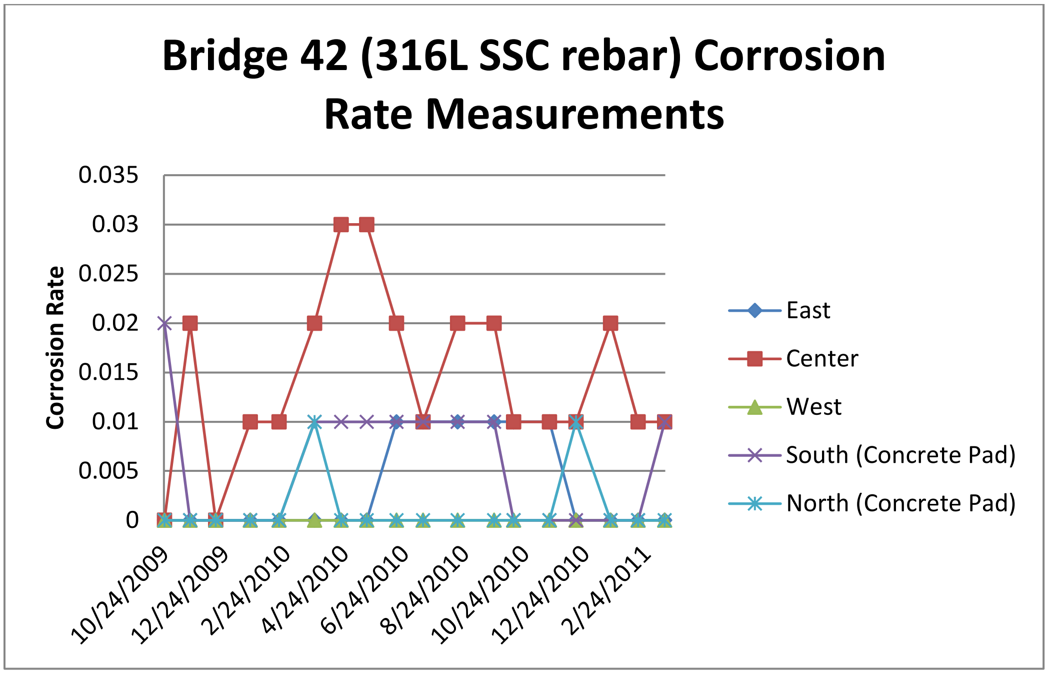
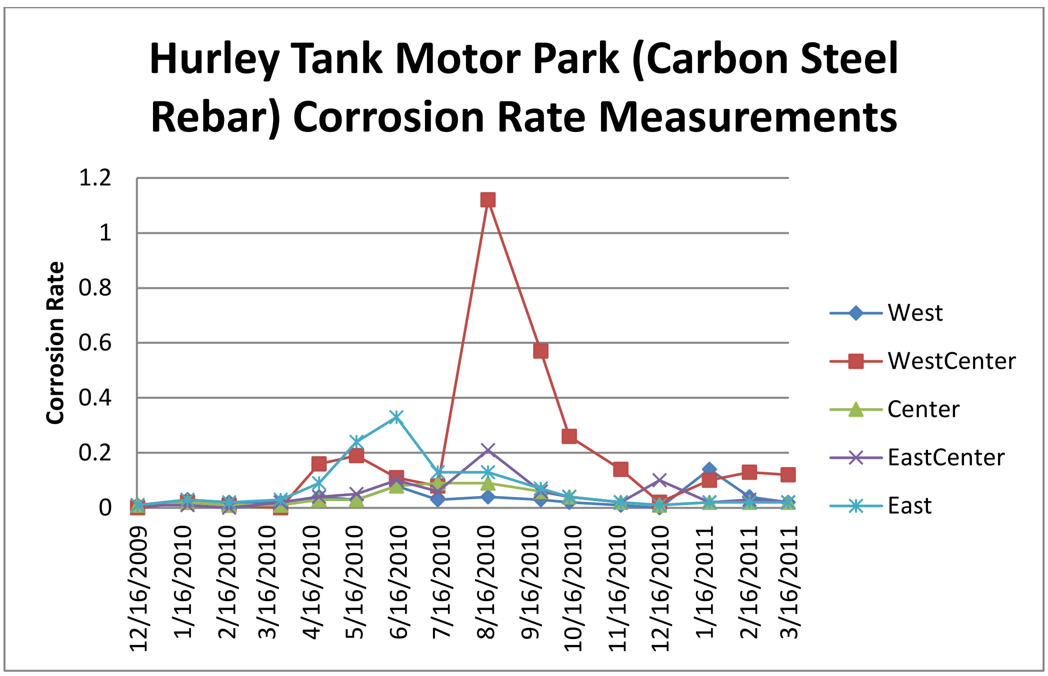


Figure 25. Carbon steel rebar (control) corrosion rate measurements for Hurley Tank Motor Park concrete pad.



3.1.3 Chloride penetration

The multidepth chloride penetration sensors were utilized in conjunction with corrosion rate sensor instrument to test for chloride penetration on both bridges and the concrete slab. Bridge 9 (Figure 26) exhibited no chloride penetration during the demonstration period. There was no detection of chloride penetration by sensors that saw only the normal base operations, nor were chlorides detected by sensors exposed to the additional deicing salts added monthly to attempt acceleration of the chloride penetration in the area above sensor 5. This procedure was started on July 2010 to accelerate the chloride penetration process for that sensor.

Since initialization, Bridge 42 exhibited no chloride activity on the three probes installed on the bridge span (Figure 27). These three probes were placed approximately two feet below the road surface. However, the two probes installed at the surface of the concrete pad had indications of chlorides. Sensor 4 had additional deicing salts added to the area above it since July 2010 (Figure 28), and activity was noted. Sensor 5 did not have additional salts added, but it still indicated the presence of moderate chlorides. Sensors 4 and 5 were located in the area where there is a shallow depression at the bottom of a steep hill and thus, the area was expected to retain salts for a longer period of time due to accumulation and runoff from the slopes that the other test areas did not have.

Hurley Tank Motor Park sensors were located on flat ground in a concrete slab (Figure 29). Some minor indications of chloride penetration were noted at first, but they appeared to have dissipated over time and were minor in nature. This indication was true even on Sensor 1, which had additional deicing salts added to the area above it since July 2010, but chloride penetration appeared to be minimal.

Figure 26. MMFX2 rebar chloride penetration measurements for Bridge 9.

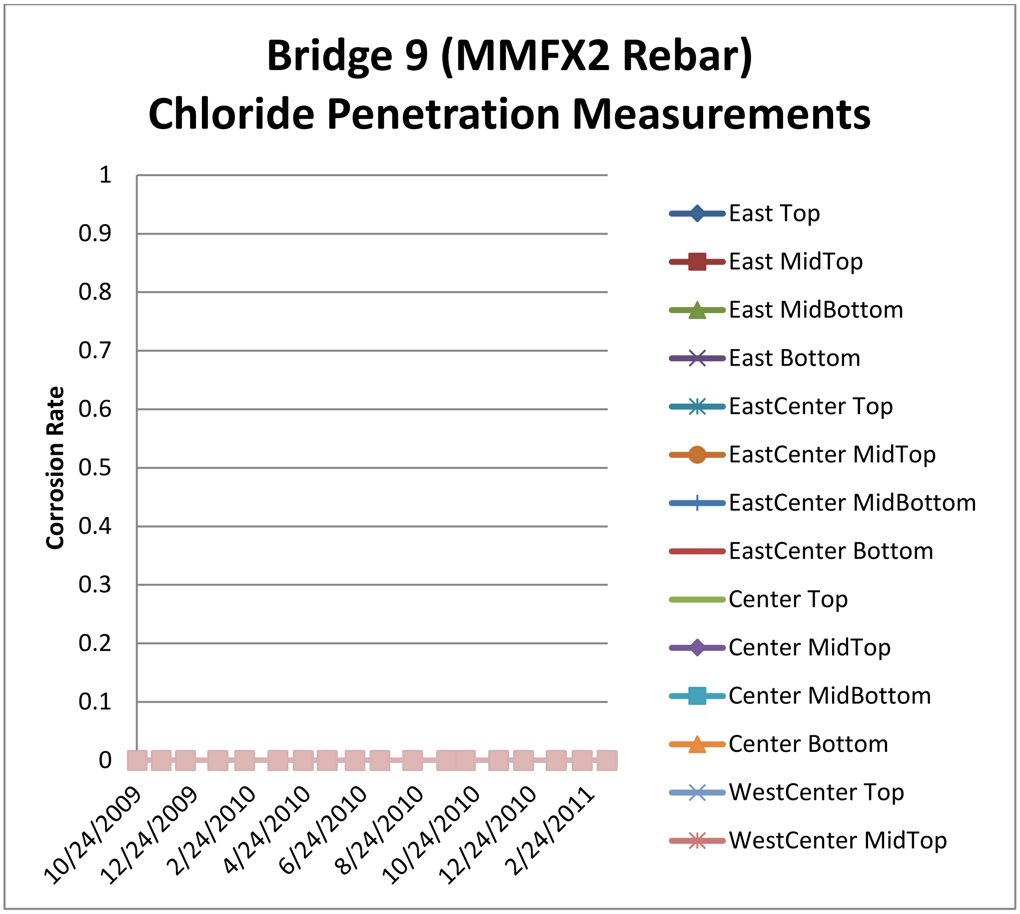


Figure 27. Chloride penetration measurements for Bridge 42, with 316L stainless steel-clad rebar.

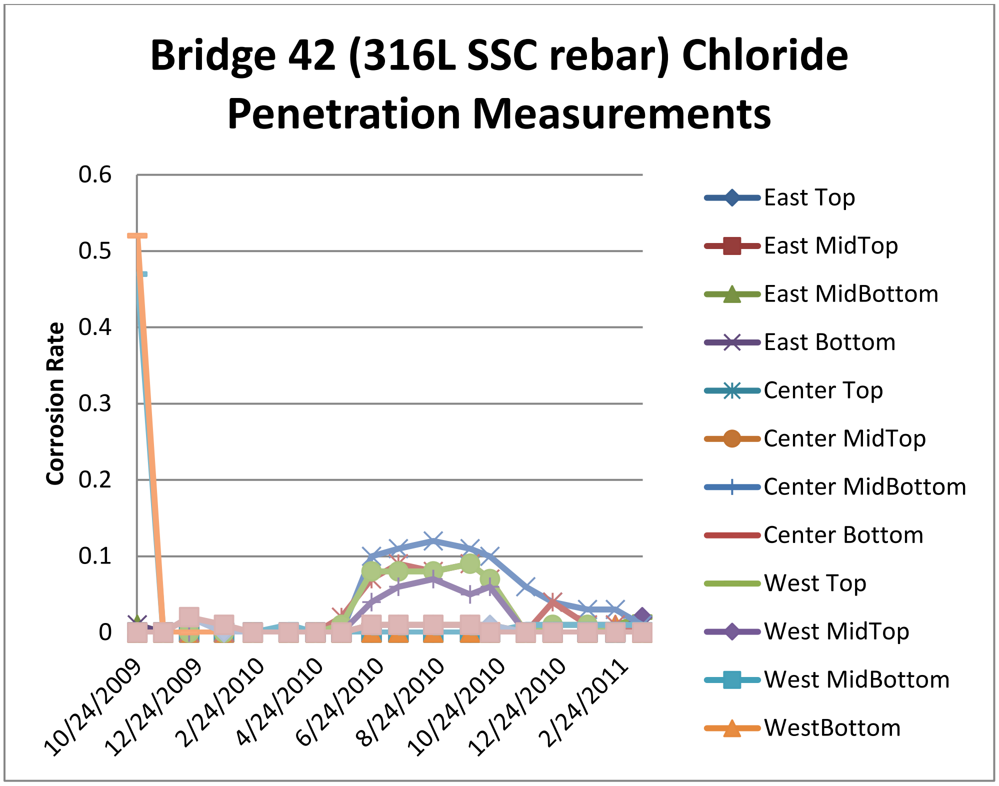
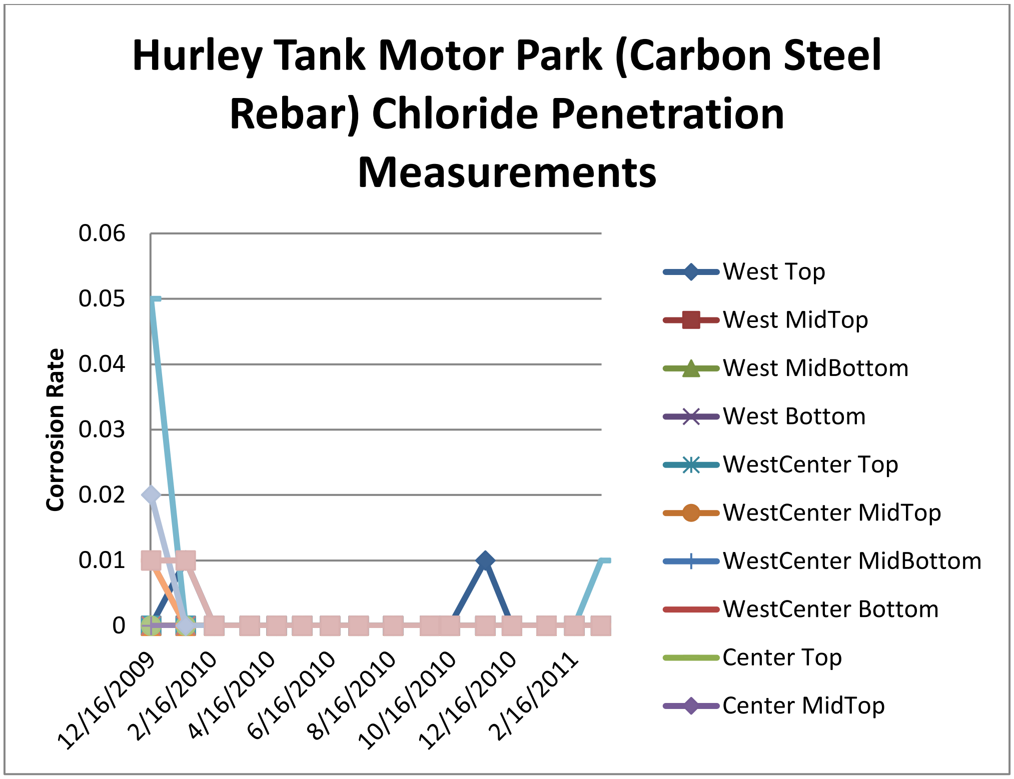


Figure 28. Area above Sensor 4 on Bridge 42 (outlined by white circle), where salt was applied.

Figure 29. Carbon steel rebar (control) chloride penetration measurements for Hurley Tank Motor Park concrete pad.



3.1.4 Exposure rack results

After 1,175 days of exposure at the MCBH test site, the plain reinforcing bar experienced extreme corrosion, as seen in Figure 30. The corrosion products were removed from the bar by hand and are shown piled next to the bar in the figure. The remaining bar measured an average of 3/8 in. in diameter, which represents a 64% reduction in cross-sectional area.

After the same exposure period and conditions, the MMFX2 rebar had a hard layer of surface corrosion, but no measureable loss in diameter (Figure 31). Upon examination, bending the bar did not appear to have a negative impact on its corrosion resistance. Based on these observations, the assumption of a 52-year service life for the bridge deck using MMFX2 rebar is justified.

Again, under the same exposure period and conditions, the SSC rebar exhibited little or no surface corrosion, with no measurable loss in diameter (Figure 32). In addition, bending the bar did not have any impact on the corrosion resistance of the bar. Based on these observations, the assumption of a 75-year service life for the bridge deck using rebar SSC is justified.

Figure 30. Plain bar after extreme exposure.

Figure 31. MMFX2 rebar after extreme exposure.

Figure 32. SSC rebar after extreme exposure.

3.2 Lessons learned

This report's conclusions and recommendation are based only on the limited data available from the monitoring period of this project. A study by the Virginia Department of Transportation (Williamson et al. 2008) determined the time to first corrosion crack initiation was 2.6 years on average for plain rebar. Approximately halfway through this project, it was decided to attempt to accelerate chloride migration by adding salt in the area of one sensor at each site. However, even this effort was unable to produce any additional data in the short time it was done (approximately 8 months), due to the time it takes for migration of chlorides.

The corrosion rate data was also marginal for making conclusions about performance. However, this data was able to show that, in the limited study, standard steel rebar was more active in showing onset of corrosion than the MMFX2 and SSC rebars. On the other hand, the data collected is not sufficient to quantify any specific expected level of improvement and performance for the advanced corrosion-resistant rebar. Continued monitoring of the sensors and data collection should easily provide the substantiated and realized benefits of the performance of using these corrosion-resistant rebar technologies.

The exposure test of the three rebars used in this evaluation in an extreme environment yielded good subjective information regarding the relative corrosion resistance of the materials. The observations from this exposure validate the corrosion resistance assumptions for these materials and also showed that bending the bars did not appear to have any adverse impact on their corrosion resistance.

An extended evaluation period of 3 to 5 years, with evaluations done on a biannual basis, is needed to help clarify the degree of performance enhancement gained for each material and the calculation of benefits expected. This longer period of evaluation would allow extrapolation of benefits over the projected design life of a structure.

4 Economic Summary

4.1 Costs and assumptions

All construction work for this project was funded by the Fort Knox DPW. Procurement of all materials except the two novel rebar materials was also done by the DPW. Contractor MEC procured the rebar materials and provided them to Fort Knox for use in bridge rehabilitation. Contractor MEC also purchased and installed all sensors and performed all monitoring and evaluation tasks. In order to compare the return on investment (ROI) values for each of the two demonstrated technologies in comparison with conventional rebar, two separate calculations were required. In each case, all costs except those of the reinforcing bars are assumed to be the same. Therefore, the actual costs for projects using either technology are allocated accordingly. The project and field demonstration costs for MMFX2 are shown in Table 1 and Table 2, and the costs for SSC are shown in Table 3 and Table 4.

Table 1. Breakdown of total project costs for MMFX2.

Description	Amount, $K
Labor	101
Materials	25
Contract to demonstrate corrosion resistant reinforcing bars	149.7
Travel	12.5
Reporting	15
Air Force and Navy participation	5
Total	308.2

Table 2. Project field demonstration costs for MMFX2.

Item	Description	Amount, $K
1	Labor for project management and execution	81.4
2	Travel for project management, installation work, and monitoring	24.2
3	Cost for sensors and rebar materials	44.1
	Total	149.7

Table 3. Breakdown of total project costs for SSC.

Description	Amount, $K
Labor	101
Materials	25
Contract to demonstrate corrosion resistant reinforcing bars	183.3
Travel	12.5
Reporting	15
Air Force and Navy participation	5
Total	341.8

Table 4. Project field demonstration costs for SSC.

Item	Description	Amount, $K
1	Labor for project management and execution	81.4
2	Travel for project management, installation work, and monitoring	24.2
3	Cost for sensors and rebar materials	77.7
	Total	183.3

ROI calculations were computed for each alternative material, each assuming that only one type of rebar was used for the project. It is assumed that the bridge is 10,000 ft^2 in size, and all costs are adjusted to account for that assumption. These standardization assumptions are necessary because, although both bridges in this project used the same amount of rebar, their designs and forms were significantly different. Those differences would have rendered costs not related to reinforcement unsuitable for purposes of developing comparative ROI projections. As noted above, then, the project management and evaluation costs for both technologies are the same projects using each alternative material. Handling and installation of the reinforcing bars are also considered to be the same except where noted below. Two ROI cases are considered: (1) MMFX2 rebar vs. plain carbon steel, and (2) SSC rebar vs. plain carbon steel.

The installation costs are assumed to be identical for all three materials (Brown, Weyers, and Wheeler 2003). Rehabilitation of an overlay includes materials, concrete removal, and traffic control, which are together assumed to cost a total of $12.93/ft^2 (Scully and Hurley 2007). An overlay is assumed to last 25 years. It is further assumed that two overlays can be performed before complete replacement is required. Since the ROIs are calculated for only 30 years, the savings realized by preventing the second overlay are not reflected in the ROI.

4.1.1 Standard carbon steel rebar vs. MMFX2

The baseline unit cost for the carbon steel used for this analysis is $1.60/ft^2, and that cost is included in the $12.93/ft^2 general rehabilitation costs referenced above. The carbon steel deck is anticipated to last 25 years, therefore one deck replacement will need to be performed 25 years after initial construction. Potholes will begin to appear 3 years after installation. Pothole repairs, including traffic avoidance costs, will be $3,000 per year starting in the third year, and those costs will increase by $100 a year until deck replacement is done for each bridge The unit costs used for MMFX2 is $2.90/ft^2 (Scully and Hurley 2007). Since material costs were paid for as part of the initial project investment, the rebar costs are subtracted from the new system costs for the first bridge.

The same amount of MMFX2 as carbon steel was used for the demonstration project. The greater strength of the MMFX2 material, however, allows for a wider spacing of rebar within the concrete structure, resulting in approximately 33% less material being used compared to carbon steel rebar (Rizkalla et al. 2005), resulting in a lowered unit cost of $1.95/ft^2. For the ROI calculations, the lower costs are assumed for future construction. The MMFX2 deck is expected to last 52 years (Kahl 2007). Pothole repairs and traffic avoidance will cost $1,500 starting in the sixth year due to the reduced corrosion and will increase by $50 a year until deck replacement for each bridge. The net benefits of using the MMFX rebar are shown under New System Benefits/Savings (column E) in Table 5.

It is further assumed that two years after initial construction, MMFX2 will be used on 20 additional bridges per year for each of two years.

4.1.2 Standard carbon steel rebar vs. stainless steel-clad rebar

The unit cost used for this analysis is $5.45/ft^2 for 316L SSC rebar (Scully and Hurley 2007). The deck with the stainless steel-clad rebar is expected to last 75 years.

The baseline unit cost for carbon steel used for this analysis is $1.60/ft^2, and this baseline cost is included in the $12.93/ft^2 general rehabilitation costs referenced above. The carbon steel deck is anticipated to last 25 years; therefore, one deck replacement will have to be performed 25 years after initial construction. Potholes will begin to appear 3 years after installation. Pothole repairs, including traffic avoidance costs, will be $3,000 per year, starting in the third year, and will increase by $100 a year until deck replacement is completed for each bridge. A unit cost of $5.45/ft^2 is used for 316L SSC rebar (Scully and Hurley 2007). Since rebar costs were paid as part of the initial project investment, the rebar costs are subtracted from the new system costs. The same amount of SSC as carbon steel was used for the demonstration project. The SSC deck is expected to last 75 years. Pothole repairs and traffic avoidance will cost $1,500 starting in the sixth year due to the reduced corrosion and increase by $50 a year until deck replacement for each bridge. The net benefits of using the SSC rebar are shown under New System Benefits/Savings (column E) in Table 6.

It is assumed that two years after initial construction, SSC will be used on 20 additional bridges per year for a two-year period.

4.2 Projected return on investment

Two ROI comparisons are provided in accordance with the standards provided in the Office of Management and Budget (OMB) circular (OMB 1992). One ROI compares MMFX2 rebar to carbon steel rebar (Table 5) and one compares 316L SSC rebar to carbon steel rebar (Table 6). As stated above, it is assumed that 10,000 ft^2 of bridge deck are being installed for each bridge.

The MMFX2 rebar showed an ROI of 7.84 vs. conventional carbon steel rebar. The SSC bar has a lower ROI of 3.86 due to its higher initial cost, which exceeds the costs of both carbon steel and MMFX2.

Table 5. ROI for MMFX2 rebar.

Return on Investment Calculation

Investment Required			308
Return on Investment Ratio	7.84	Percent	784%
Net Present Value of Costs and Benefits/Savings	4,319	6,736	2,417

A Future Year	B Baseline Costs	C Baseline Benefits/Savings	D New System Costs	E New System Benefits/Savings	F Present Value of Costs	G Present Value of Savings	H Total Present Value
1							
2	130		114		100	114	14
3							
4	2,758		2,818		2,150	2,104	-46
5	2,841		2,903	3	2,070	2,028	-42
6				3		2	2
7				63		39	39
8				125		73	73
9				129		70	70
10				119		60	60
11				108		51	51
12				110		49	49
13				112		46	46
14				114		44	44
15				116		42	42
16				118		40	40
17				120		38	38
18				122		36	36
19				124		34	34
20				126		33	33
21				128		31	31
22				130		29	29
23				132		28	28
24				134		26	26
25				136		25	25
26				139		24	24
27	136			137		44	44
28				139		21	21
29	5,775			70		822	822
30	5,949			3		782	782

Table 6. ROI for 316L SSC rebar.

Return on Investment Calculation

Investment Required			342
Return on Investment Ratio	3.86	Percent	386%
Net Present Value of Costs and Benefits/Savings	5,439	6,758	1,319

A Future Year	B Baseline Costs	C Baseline Benefits/Savings	D New System Costs	E New System Benefits/Savings	F Present Value of Costs	G Present Value of Savings	H Total Present Value
1							
2	130		114		100	114	14
3							
4	2,758		3,566		2,721	2,104	-616
5	2,841		3,673	3	2,619	2,028	-591
6				3		2	2
7				63		39	39
8				125		73	73
9				129		70	70
10				119		60	60
11				108		51	51
12				110		49	49
13				112		46	46
14				114		44	44
15				116		42	42
16				118		40	40
17				120		38	38
18				122		36	36
19				124		34	34
20				126		33	33
21				128		31	31
22				130		29	29
23				132		28	28
24				134		26	26
25				136		25	25
26				139		24	24
27	272			137		66	66
28				139		21	21
29	5,775			70		822	822
30	5,949			3		782	782

5 Conclusions and Recommendations

5.1 Conclusions

The corrosion data collected from the three sites indicates that MMFX2 and 316L SSC rebar materials are less active and therefore more corrosion-resistant in relation to standard carbon steel rebar. The performance period for this study was not long enough to collect data that would allow more conclusive performance results for each of the rebar technologies being evaluated. The data that was developed, however, showed the advanced corrosion-resistant rebar will outperform standard rebar. Given that initial assessment, it can be stated that initial costs may be higher for using the advanced materials, but that higher first cost may be deemed justifiable considering related cost factors of down time, loss of efficiency, loss of a critical structure, and replacement, as shown in the ROI analysis (section 4.2). A consideration of the costs versus additional life span of the structure is necessary for a complete evaluation.

Based on data collected and the time frame of the test period, indications are that the corrosion-resistant properties of MMFX2 and 316L SSC rebar are performing at a high level. Comparison to the standard carbon steel rebar indicates that these two materials will extend the service life of structures used in high-salt exposure, such as those managed in winter with deicing salts as the two subject bridges are. However, further monitoring of the three sites is recommended to develop more conclusive data. The penetration time of chlorides and onset of corrosion in rebar in structures of this type is considerably longer than the time allotted in this project to evaluate completely the full degree of increased effectiveness of the two corrosion-resistant rebar materials evaluated.

Also, a nonstandard exposure test of the three materials showed little to no section loss in the MMFX2 and SSC rebars, whereas plain steel experienced a section loss of approximately 64%. This additional test validates the assumptions and results obtained from the demonstration project.

5.2 Recommendations

5.2.1 Applicability

Preliminary observations of the tested materials indicated that MMFX2 and 316L SSC rebar showed superior corrosion-resistant properties to those of standard carbon steel rebar. These observations, however, are based on the limited time frame allotted for this evaluation. Rebar corrosion, associated with salt environments, is a slow process and may take years to progress to an aggressive level. An extended evaluation period of 3 to 5 years, with evaluations done on a biannual basis, is needed to help clarify the degree of performance enhancement gained for each material and the calculation of benefits expected. This longer period of evaluation would allow extrapolation of benefits over the projected design life of a structure.

Costs and availability will also need to be evaluated before selecting any new rebar materials. Both MMFX2 and 316L SSC rebar cost more than standard steel rebar. In the more aggressive of corrosive environments, the additional expense would be cost effective. This cost effectiveness is primarily important for a critical structure that needs to remain in continuous operation. SSC rebar was found to be the most expensive and most difficult material to procure. It also had the longest lead time on manufacturing. Expense and lead time are significant points to consider when evaluating materials. MMFX2 rebar showed equal corrosion-resistant properties to SSC rebar, but at a lesser cost.

5.2.2 Implementation

As stated above, further testing would be advisable before implementing a major change in rebar selection, to ensure that long-term strength and durability are not being compromised. Further testing also would give additional time for chloride penetration to occur and for effects on the tested material to be manifested. Should future data support the current trends of the two new products having better corrosion resistance and therefore offering a longer design life than standard carbon steel rebar, a review of three DoD criteria documents was conducted, with one recommendation for change as noted below.

No changes to Army TM 5-600 (1994) and UFC 3-250-04 (2009) are necessary in order to employ the new rebar materials. For UFC 3-250-01FA (2004), it is recommended to change Section 13-4 Reinforcing Steel, paragraph a. The paragraph currently ends by stating “The use of epoxy coated steel may be considered in areas where corrosion of the steel may be a problem.” It is recommended that the paragraph be updated to read “The use of MMFX2, 316L stainless steel-clad steel, or epoxy-coated steel should be considered in areas where corrosion of the steel may be a problem. A life-cycle cost analysis between potential alternatives should be performed to determine the best choice of material by project."

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Appendix: Corrosion Sensor Locations

The following drawings are the schematics for sensor locations, as placed on Bridge #9, Bridge #42, and Hurley Tank Motor Park at Fort Knox, Kentucky.

Figure A1. Sensor schematic for Bridge 9 at Fort Knox, KY.

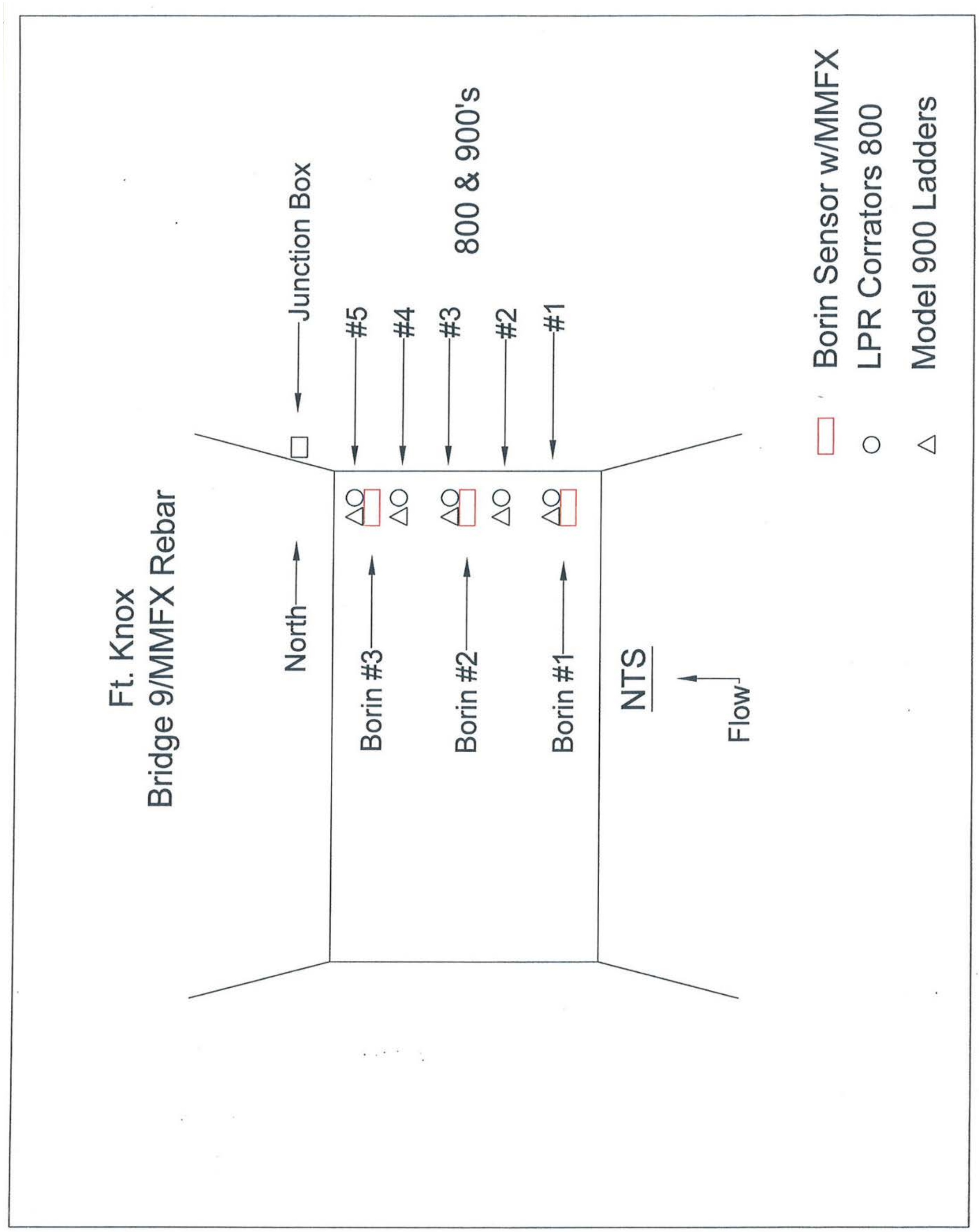


Figure A2. Sensor schematic for Bridge 42 at Fort Knox, KY.

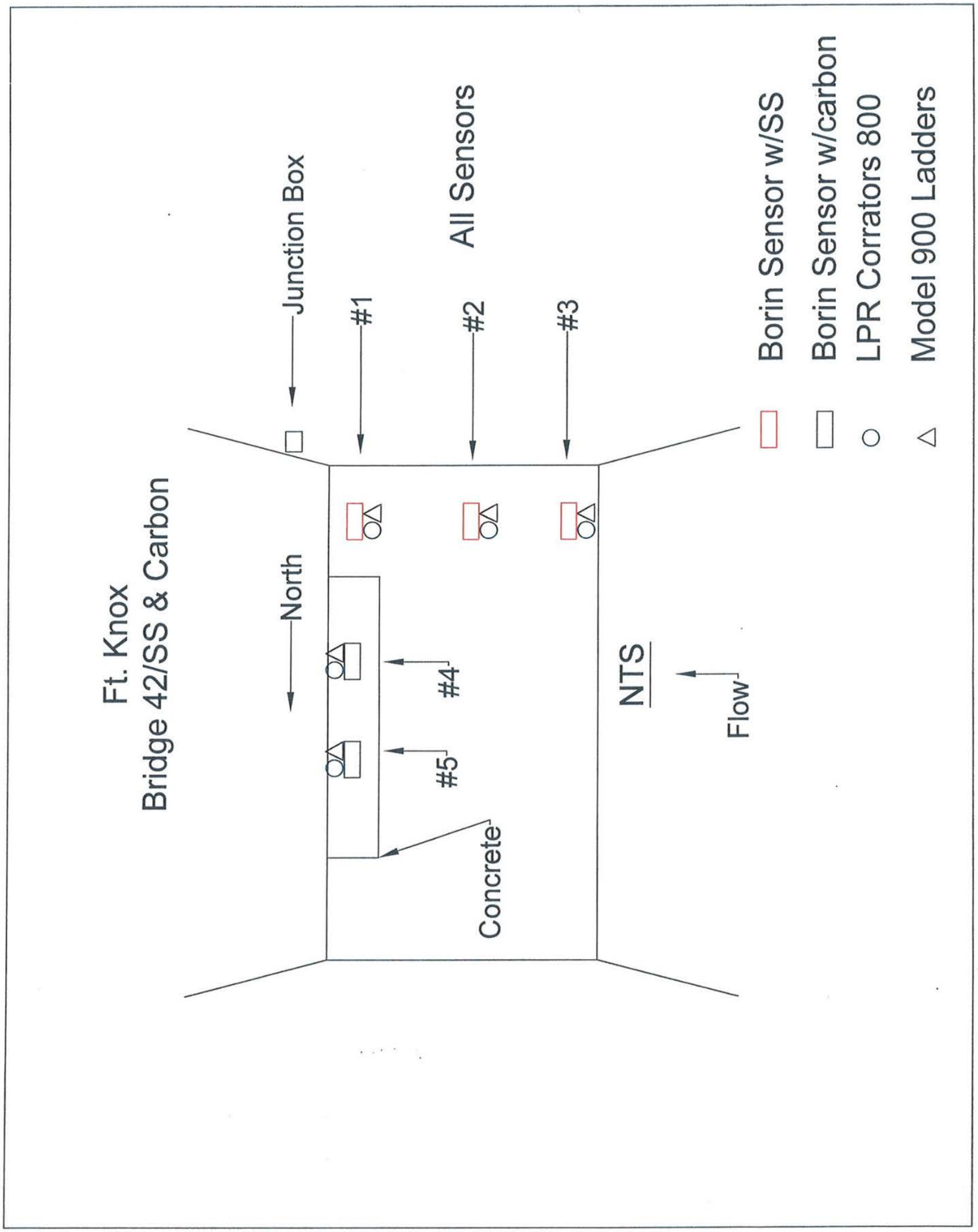


Figure A3. Sensor schematic for Hurley Tank Motor Park at Fort Knox, KY.

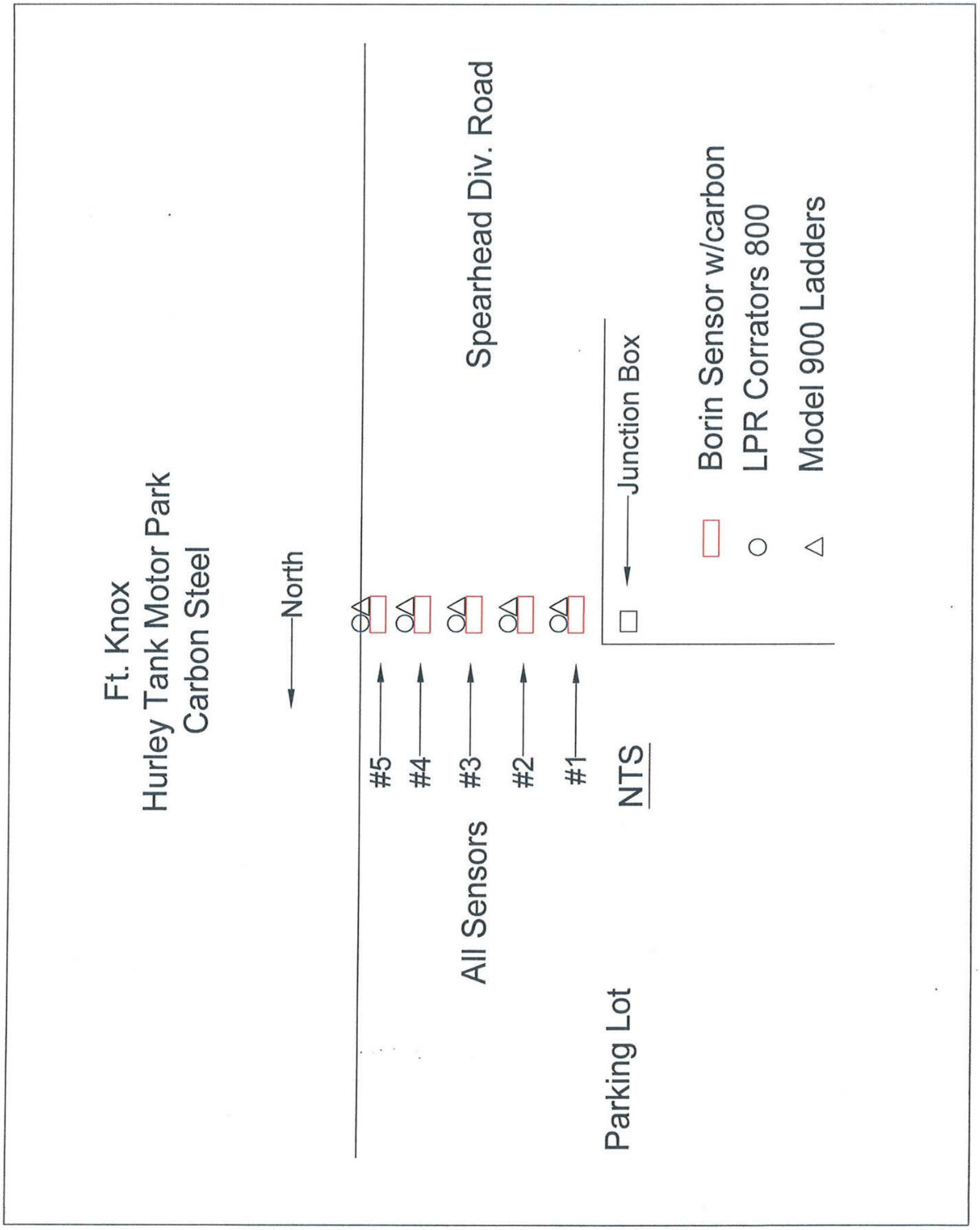
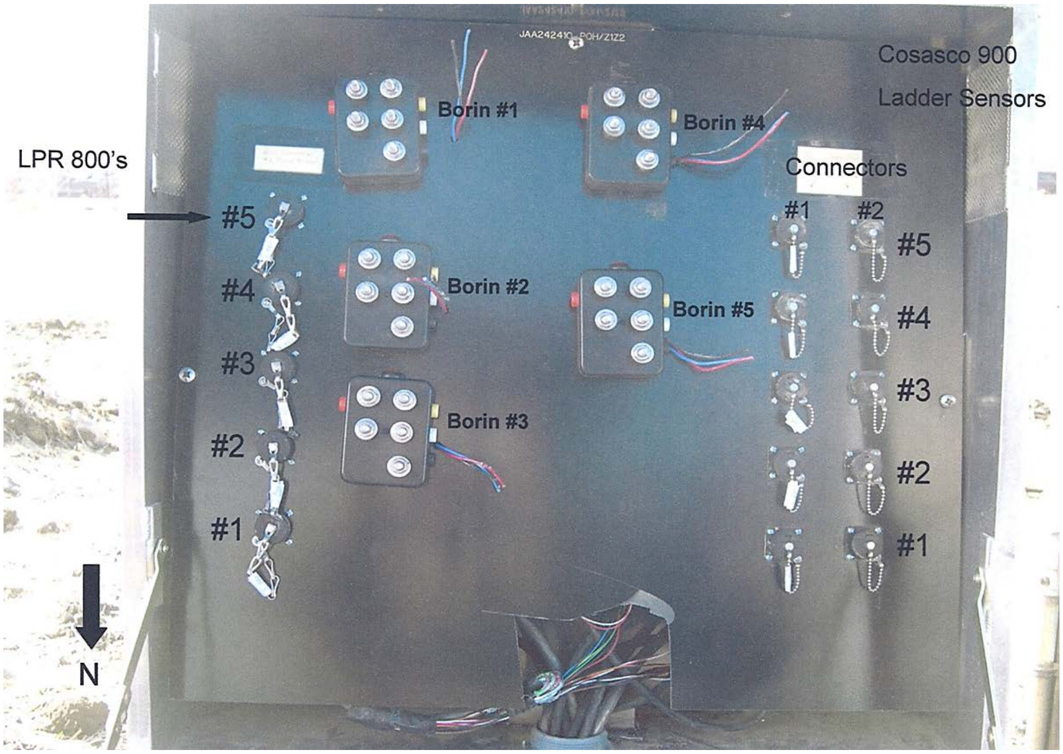


Figure A4. Example of junction box layout for three types of sensors, shown for Hurley Tank Motor Park, Fort Knox, KY.



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14. ABSTRACT

Military installations maintain networks of roads and bridges that comprise basic, mission-critical infrastructure required for everyday operations. Many reinforced concrete bridges are long overdue for repair or replacement due to various stressors and corrosion mechanisms that have degraded the steel reinforcement and, therefore, reduced load-carrying capacity. These stressors include cyclic loading, freeze/thaw cycles, and penetration of water and road deicing salts that greatly accelerate both corrosion and concrete fracturing. This report presents the findings of a demonstration/validation project at Fort Knox, KY, in which two different advanced corrosion-resistant reinforcement materials were used in reconstructed concrete bridge decks.

Material performance was monitored for 18 months using sensors to return data on corrosion potential, corrosion rate, and chloride penetration thresholds. These data also were collected from a control structure reinforced with conventional carbon steel rebar, and analyses were executed to compare material performance. Exposure testing of material specimens in highly corrosive environments was performed concurrently. Both demonstrated rebar materials have shown good corrosion resistance in the bridge decks and exposure coupon racks. Continuing periodic observation of the demonstration structures is recommended to produce more definitive performance results. Economic analysis of both materials show a positive return on investment over carbon steel rebar.

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